Climate Dynamics (2001) 18: 297–302

O. Boucher · J. Haywood

On summing the components of radiative forcing of climate change

Received: 14 March 2001 / Accepted: 1 June 2001

Abstract Radiative forcing is a useful concept in determining the potential influence of a particular mechanism of climate change. However, due to the increased number of forcing agents identified over the past decade, the total radiative forcing is difficult to assess. By assigning a range of probability distribution functions to the individual radiative forcings and using a Monte-Carlo approach, we estimate the total radiative forcing since pre-industrial times including all quantitative radiative forcing estimates to date. The resulting total radiative forcing has a 75–97% probability of being positive (or similarly a 3–25% probability of being negative), with mean radiative forcing ranging from +0.68 to +1.34 W m^{-2}, and median radiative forcing ranging from +0.94 to +1.39 W m^{-2}.

1 Introduction

Radiative forcing (RF) enables estimation of the potential climatic effect of a particular perturbation to the energy balance of the Earth/atmosphere system. Many modelling studies of varying complexity indicate that the global mean temperature response, ΔT, to a global mean RF, ΔF, may be estimated using the relationship:

$$\Delta T = \lambda \Delta F \qquad (1)$$

where λ is the climate sensitivity of the particular model in K/(W m^{-2}). While the climate sensitivity parameter varies between models, it appears approximately independent of the sign, magnitude, and spatial distribution of the RF (Ramaswamy and Chen 1997a; Le Treut et al. 1998; Hansen et al. 1998; Forster et al. 2000).

There have been significant advances in our understanding of RF mechanisms. IPCC (1990) and IPCC (1994) presented estimates for well-mixed greenhouse gases (CO_2, CH_4, N_2O, and the halocarbons), stratospheric and tropospheric ozone, the direct and indirect effect of anthropogenic aerosols, and solar activity. Shine et al. (1996) in IPCC (1996) separated the direct effect of aerosols into sulfate, fossil-fuel soot, and biomass burning. Ramaswamy et al. (2001) in IPCC (2001) added fossil-fuel organic carbon, mineral dust, contrails, aircraft induced cirrus, and the effects of land-use change upon the albedo of the Earth. Note that Ramaswamy et al. (2001) only considered the first indirect aerosol effect (an increase in cloud albedo due to an increase in cloud droplet number concentration at fixed liquid water content) and not the second one (a possible increase in cloud liquid water content and cloud cover associated with a decrease in precipitation efficiency). In Fig. 1, best estimates of the RF from pre-industrial (~1750) to present (late 1990s; ~2000) times are shown by the rectangular bars, with vertical lines indicating the uncertainty which is guided for the most part by the range of published estimates. Exceptions are for mineral dust, aviation induced cirrus, and the first indirect effect of tropospheric aerosols. For mineral dust and the first aerosol indirect effect, no best estimate is presented owing to the large uncertainties associated with the mechanisms. The range given for the first aerosol indirect effect is broader than the range of model results to account for uncertainties in model parametrisations and neglect of in-cloud absorption by black carbon aerosols (Ramaswamy et al. 2001). Note that Shine and Forster (1999) did not account for uncertainties related to in-cloud absorption, and suggested a best estimate of −1 W m^{-2} and a factor of two uncertainty. For aviation-induced cirrus, the range represents a range of best estimates and does not involve uncertainties which could

---

O. Boucher (✉)
Laboratoire d'Optique Atmosphérique,
U.F.R. de Physique, Bâtiment P5,
Université des Sciences et Technologies de Lille,
59655 Villeneuve d'Ascq Cedex, France
On sabbatical leave at the Max Planck
Institute for Chemistry, Mainz, Germany
E-mail: boucher@loa.univ-lille1.fr

J. Haywood
Meteorological Office, London Road, Bracknell, UK

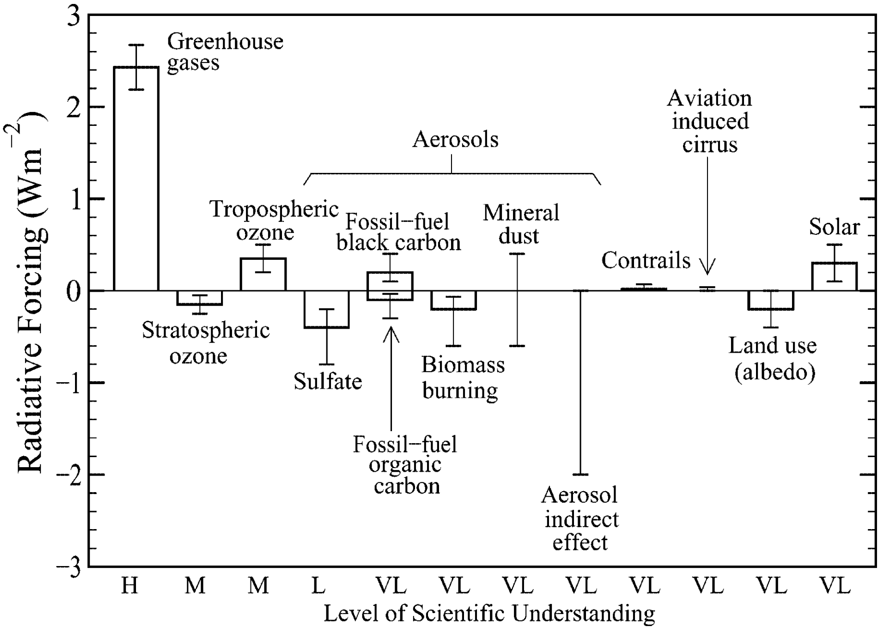

Fig. 1 Global, annual-mean radiative forcing (W m^{-2}) due to a number of agents from pre-industrial (1750) to present (late 1990s; ~2000) times. *H*, *M*, *L*, and *VL* are the different *LOSU* and stand for "high", "medium", "low", and "very low", respectively. Adapted from Ramaswamy et al. (2001)

Table 1 Radiative forcings (W m^{-2}) from pre-industrial (~1750) to present (late 1990s; 2000) times as given in Ramaswamy et al. (2001) and used in this study

Forcing agent	IPCC best estimate (W m^{-2})	Uncertainty or range (W m^{-2})	Mean value (normal PDF) (W m^{-2})	Mean values (log-normal PDFs) $x = 1.0/x = 1.5/x = 2.0$	Mean value (flat PDF) (W m^{-2})
Greenhouse gases	+2.43	±10%	+2.43	NA	NA
Stratospheric ozone	−0.15	±0.10	−0.15	NA	NA
Tropospheric ozone	+0.35	±0.15	+0.35	NA	NA
Sulfate aerosols	−0.40	×2	−0.50	−0.508/−0.445/−0.425	NA
Fossil-fuel organic carbon	−0.10	×3	−0.167	−0.183/−0.131/−0.116	NA
Fossil-fuel black carbon	+0.20	×2	+0.25	+0.254/+0.222/+0.212	NA
Biomass burning aerosols	−0.20	×3	−0.333	−0.365/−0.261/−0.233	NA
Mineral dust	NA	−0.6 to +0.4	−0.10	NA	−0.10
Aerosol indirect effect	NA	−2.0 to 0	−1.00	−1.220/−0.872/−0.776[b]	−1.00
Contrails	+0.02	×3.5	+0.038	+0.044/+0.028/+0.024	NA
Aviation-induced cirrus	NA	0 to +0.04[a]	+0.02	NA	+0.02
Land-use (albedo)	−0.20	±100%	−0.20	NA	NA
Solar	+0.30	±0.20	+0.30	NA	NA

NA means "not applicable"

The mean radiative forcing, RF_{mean}, assuming a log-normal PDF is related to the best estimate radiative forcing, $RF_{best\_estimate}$, the uncertainty factor, and x through the relationship: $RF_{mean} = RF_{best\_estimate} \exp((\ln(\text{uncertainty\_factor})/x)^2/2)$

[a] The range 0 to 0.04 W m^{-2} given in IPCC (1999, 2001) is a range of best estimate, but we use it here as a range of uncertainty

[b] For the log-normal PDF of the aerosol indirect effect, we assume a best estimate value of −0.667 W m^{-2} and a factor of 3 uncertainty

not be quantified (IPCC 1999). We ignore the RF due to stratospheric volcanic aerosols because of its episodic and transient nature. A qualitative level of scientific understanding (LOSU) was included for each mechanism to provide a subjective judgement of the scientific grounding on which each of the estimates is made (Ramaswamy et al. 2001).

The total RF since pre-industrial times and its sign are of central importance to climate modelling studies because, according to Eq. (1), a negative net RF leads to a surface cooling while a positive net RF leads to a surface warming. Models have been used to combine different RFs and simulate the past temperature change, the complexity of the models ranging from simple energy balance models (e.g. Raper and Cubasch 1996) to fully coupled atmosphere-ocean general circulation models (e.g. Meehl et al. 2000). While Shine et al. (1996) and Ramaswamy et al. (2001) did not derive a 'best estimate' of the total RF, Schwartz and Andreae (1996) provided a 'best estimate' RF by summing the individual best estimates, and an uncertainty range by summing the upper and lower ends of the individual uncertainty ranges. This study extends the study of Schwartz and Andreae (1996) by including all RF agents identified by Ramaswamy et al. (2001). We assume probability density functions (PDFs) for each RF mechanism and a total probability density function (TPDF) is obtained by combining these PDFs using a Monte-Carlo modelling technique. The mean and median of the TPDF, as well as the probability that the total RF is negative, are computed.

2 Method

As summarized in Table 1, the uncertainties in Ramaswamy et al. (2001) are given either as a range (e.g. for greenhouse gases, stratospheric and tropospheric ozone) or as an uncertainty factor (e.g. for sulfate aerosols or contrails). Three basic functions are used in this study to represent the PDF of the individual RF component: the normal PDF, the log-normal PDF, and the equally probable or 'flat' PDF. Figure 2 shows these PDFs for the RF of sulfate aerosols which is given a best estimate of −0.4 W m^{-2} and an uncertainty factor of 2 in Ramaswamy et al. (2001). The solid line on Fig. 2 shows a normal PDF centred on −0.5 W m^{-2} with 2 standard deviations encompassing the range −0.2 to −0.8 W m^{-2} (i.e. $2\sigma = 0.3$ W m^{-2}). The dashed line shows a log-normal PDF which expresses the fact that the logarithm of the (magnitude of the) RF is normally distributed around ln(0.4) with a standard deviation verifying $2\sigma = \ln(0.4) - \ln(0.2) = \ln(0.8) - \ln(0.4) = \ln(2)$. The dotted line shows a flat PDF encompassing the range −0.2 to −0.8 W m^{-2}. Note here that, although the ranges are constrained in a consistent way, the means of the normal and log-normal PDFs shown in Fig. 2 are not identical. They are −0.5 and −0.425 W m^{-2} for the normal and the log-normal PDFs, respectively, and differ from the best estimate. The log-normal PDF is probably the best representation of the mean and range of those RFs quoted by Ramaswamy et al. (2001) '*as uncertain by a factor of y*'. It also constrains the sign of the forcing, which is not the case when a (broad) normal PDF is used.

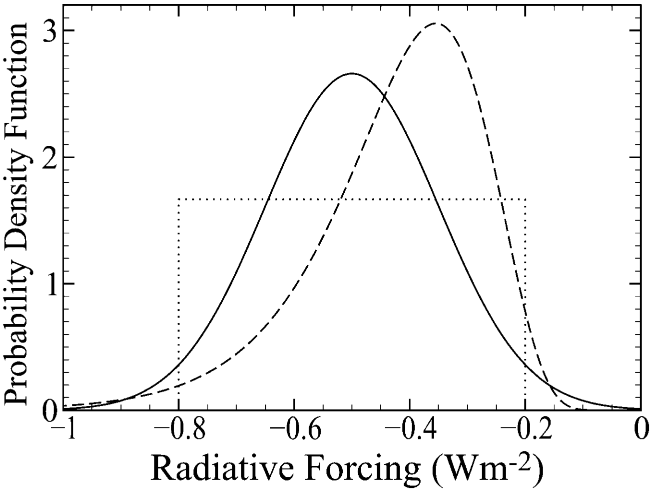

Fig. 2 Illustration of the three basic probability distribution functions (PDFs) used for the direct aerosol radiative forcing by sulfate aerosols. The normal (*solid line*) and log-normal (*dashed line*) PDFs are for $x = 2.0$. The flat PDF (*dotted line*) is shown for completeness but is not used in the present study for sulfate aerosols

We restrict ourselves to the forcing agents identified by Ramaswamy et al. (2001) and to the period from pre-industrial to present times. A similar analysis could be conducted for the past time history of RFs (Myhre et al. 2001) and for the future RFs estimated from the IPCC emission scenarios (Ramaswamy et al. 2001). Different scenarios are set up where one of the three PDFs is assigned to each RF component shown in Fig. 1. The normal and log-normal PDFs are set up so that the range given by Ramaswamy et al. (2001) encompasses the mean ± x standard deviations (Table 1). As Ramaswamy et al. (2001) state that the range is based on values in the published literature, our calculations assume x values of 1.0, 1.5, and 2.0. Thus when normal and log-normal PDFs are used, the ranges in Ramaswamy et al. (2001) are interpreted as representing the 68%, 87%, or 95% confidence intervals, respectively. The flat PDF assumes an equally probable likelihood that the RF lies within the range given by Ramaswamy et al. (2001). A Monte-Carlo simulation is performed, where we generate 1 million vectors composed of the 13 RF components of Fig. 1. As mentioned, each RF component is treated as a random variable which follows an assumed PDF (as defined in Tables 1 and 2). A new random variable (the total RF) is defined as the sum of the 13 RF components, for which we obtain a PDF (called the TPDF). In this procedure, we assume that the different RFs can be considered as independent, which may not be entirely valid.

Three simulations (referred to as 1.0, 1.5, and 2.0 corresponding to x values of 1.0, 1.5, and 2.0, respectively) are performed for each of four scenarios. In scenario A, all the RFs are assumed to follow normal PDFs (Table 2). Scenario B is as scenario A, but those RFs quoted by Ramaswamy et al. (2001) as '*uncertain by a factor of y*' (the RF by contrails and the direct aerosol RFs, except that due to mineral dust) are modelled by log-normal PDFs. Implementation of these scenarios skews the PDF for each component toward the best guess of Ramaswamy et al. (2001). Scenario C is as scenario B, but RFs with no best estimate (first indirect aerosol effect, mineral dust, and aviation induced cirrus) are modelled by flat PDFs. Scenario D is as scenario C, but with the first indirect aerosol RF being modelled by a log-normal PDF.

3 Results

Figure 3a–c shows the results of the simulations for $x = 1.0$, $x = 1.5$, and $x = 2.0$, respectively. The TPDF curves in Fig. 3 are not entirely smooth due to the use of a statistical Monte-Carlo model in determining each PDF. However, multiple computations with the Monte-Carlo model suggest that the mean, median, and probability of negative forcing shown in Table 3 are accurate to 0.005 W m^{-2}, 0.01 W m^{-2}, and 0.1%, respectively.

Table 2 Summary of the PDFs for individual RFs in scenarios A to D

Scenario	Greenhouse gases, land-use and solar			Direct aerosol effect (except mineral dust) and contrails			Mineral dust and aviation-induced cirrus			First aerosol indirect effect		
	N	LN	F	N	LN	F	N	LN	F	N	LN	F
A	X			X			X			X		
B	X				X		X			X		
C	X				X				X			X
D	X				X				X		X	

N, LN, and F stand for 'normal', 'log-normal', and 'flat' PDF, respectively

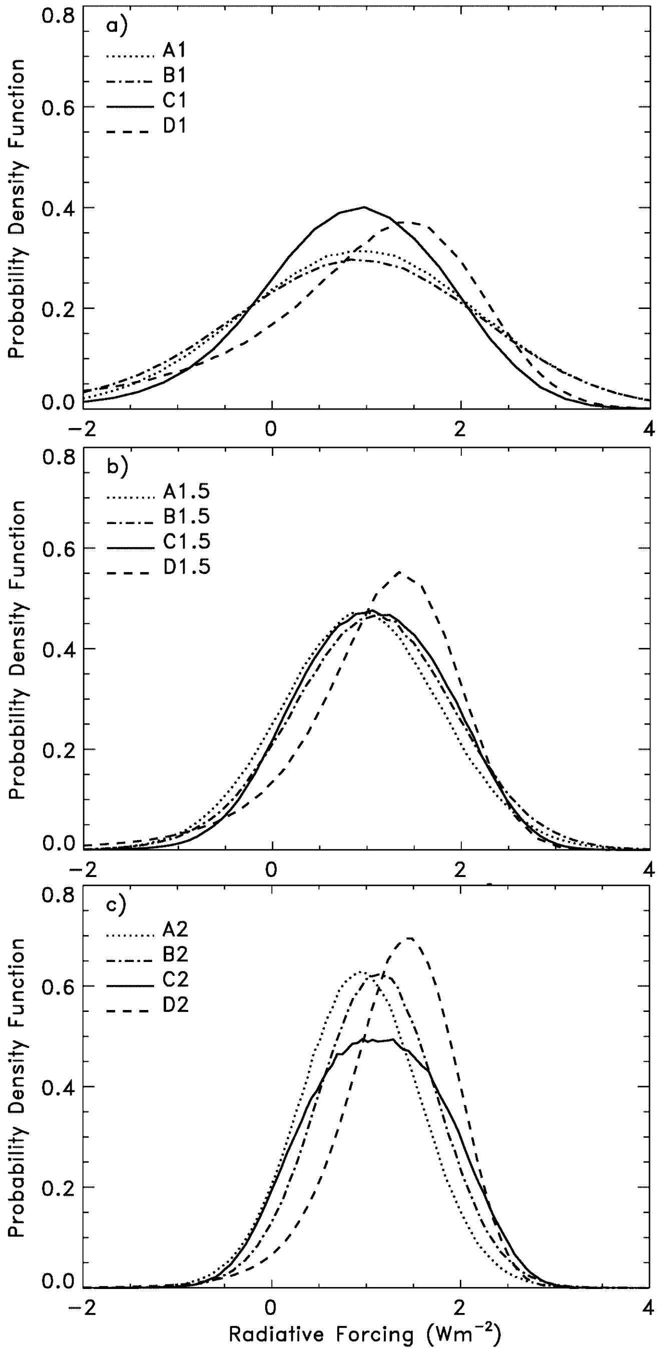

Fig. 3a–c Probability distribution functions of the total radiative forcing for the 12 simulations described in the text: **a** $x = 1.0$, **b** $x = 1.5$, and **c** $x = 2.0$

We have verified that the Monte-Carlo approach yields the expected results for simulations A, where the TPDF can be computed analytically, and that for each simulation the mean total RF obtained with the Monte-Carlo calculations is identical to the sum of the individual mean RFs.

The mean total RF is very sensitive to the assumed value for x (Table 3). It ranges among the scenarios from 0.68 to 0.94 W m^{-2}, 0.94 to 1.19 W m^{-2}, and 0.94 to 1.34 W m^{-2}, for x values of 1.0, 1.5, and 2.0, respectively. Except for simulations of scenario A, the median is larger than the mean total RF because the log-normal PDFs are primarily applied to RFs that are negative, which skews the TPDFs to larger RFs. Note that the median, which may be more relevant than the mean, is never smaller than 0.94 W m^{-2}.

The only difference between the simulations from the C and D scenarios is that the PDF for the first aerosol indirect effect is changed from a flat PDF (range −2 to 0 W m^{-2}) to a log-normal PDF (with 68%, 87, or 95% confidence intervals for the range −0.22 to −2.0 W m^{-2}). While both PDFs appear reasonable, the effects upon the TPDF are significant. The median total RF is much larger in the D compared to the C simulations. Also the probability for negative total RF is either much larger (when $x = 1.0$) or much smaller (when $x = 2.0$) in the D compared to the C scenario.

We compute the probability that the total RF is negative to range between 2.8% and 24.7%. Similarly the total RF has a 75.3 to 97.2% probability of being positive. If we follow IPCC (2001) to indicate confidence estimates, this means that the total RF is unlikely (10–33% chance) or very unlikely (1–10% chance) to be negative.

4 Discussion and conclusion

The arguments for not summing the radiative forcings from the different forcing mechanisms rely on the following arguments:-

a. The uncertainty range given for each RF is not a statistically rigorous quantity. The ranges are for the most part guided by the spread in the published estimates of RFs, but in some cases (e.g. anthropogenic mineral dust, or first aerosol indirect effect) they also reflect a subjective assessment of the uncertainties. Performing rigorous statistical analysis of the results from the models is difficult because of the small number of studies, and because several of the modelling studies are not truly independent. Attempts to estimate the uncertainty in the aerosol RF using simplified expressions (e.g. Charlson et al. 1992; Penner et al. 2001) make simplifying assumptions which may limit their applicability.

b. The presence of RF estimates where no best estimate is provided such as for aviation induced cirrus, anthropogenic mineral dust, and the first aerosol indirect effect makes such a summation difficult.

c. The different LOSU afforded to each of the forcing mechanisms complicate the issue. It may be argued that RFs with very low LOSU should be given a lower weighting than those with a high LOSU.

d. Because of a complex spatial distribution, the global-mean total RF does not give sufficient information on the spatial response of the climate system. Thus even for a global mean RF of zero, there may be sig-

Table 3 Mean and median total radiative forcing (W m^{-2}) and probability that the total radiative forcing is negative (%) for the 12 simulations presented in the text

Simulation	Mean radiative forcing (W m^{-2})	Median radiative forcing (W m^{-2})	Probability that radiative forcing is negative (%)
A1.0	0.94	0.94	23.0
B1.0	0.89	0.94	24.7
C1.0	0.89	0.96	17.7
D1.0	0.67	1.10	22.7
A1.5	0.94	0.94	13.5
B1.5	1.06	1.07	10.9
C1.5	1.06	1.07	8.9
D1.5	1.19	1.32	8.5
A2.0	0.94	0.94	7.1
B2.0	1.11	1.11	4.2
C2.0	1.11	1.11	6.0
D2.0	1.34	1.39	2.8

nificant local changes in climate (Cox et al. 1995; Ramaswamy and Chen 1997b).

e. The additivity of the climate responses to different RFs, which is the central justification for a summation of RF, has been shown for some but not all of the RF mechanisms (e.g. Ramaswamy and Chen 1997a; Hansen et al. 1998).

By performing a set of simulations using different PDFs (as discussed in Sect. 2) and presenting an ensemble of results we circumvent arguments (a) and (b). While we temporarily add a level of complexity by choosing different sets of PDFs, we can draw in the end more robust conclusions because they apply to the whole set of simulations. It is difficult to justify argument (c) as if a forcing mechanism is identified as scientifically valid and assigned a very low LOSU, it should not simply be discarded or assigned a reduced weighting, but should be treated in a manner consistent with the rest of the RF mechanisms (Penner and Rotstayn 2000). Argument (d) may be rebuffed as RF has never been intended to be an indicator of regional climate change. If the climate sensitivity parameter varies for different RFs, or combinations of RFs (argument e), then the whole concept of RF as an indicator of potential climate change is flawed. While some studies show that the climate sensitivity parameter may differ for some RF mechanisms such as absorption by black carbon aerosols (e.g. Hansen et al. 1998), these forcing mechanisms should currently be considered as exceptions to the rule, given the number of studies that have shown the relationship between global mean temperature response and global mean RF as being relatively robust.

Some simulations represent a better interpretation of the conclusions of Ramaswamy et al. (2001) than others. Simulations A and B assume a normal distribution for the first aerosol indirect RF. One consequence is that it allows positive values for this forcing, which becomes more probable as x decreases. This is not realistic and we believe that the C and D simulations are better representations of Ramaswamy et al. (2001). It is difficult to select a best value for x, but there are some limited indications that values of 1.5 or 2.0 are more appropriate than a value of 1.0. Analysis of the published estimates of the direct sulfate aerosol RF, as compiled by Ramaswamy et al. (2001), reveals a mean of -0.45 W m^{-2} and a standard deviation of 0.18 W m^{-2} ($n = 19$), which would roughly correspond to $x = 1.7$. A similar analysis for the tropospheric ozone RF yields a mean of 0.35 W m^{-2} and a standard deviation of 0.05 W m^{-2} ($n = 11$), corresponding to $x = 3.0$. These simple statistics cannot be carried out for the other RF agents because of the lack of suitably large samples. If one rejects (somewhat subjectively) an x value of 1.0 and

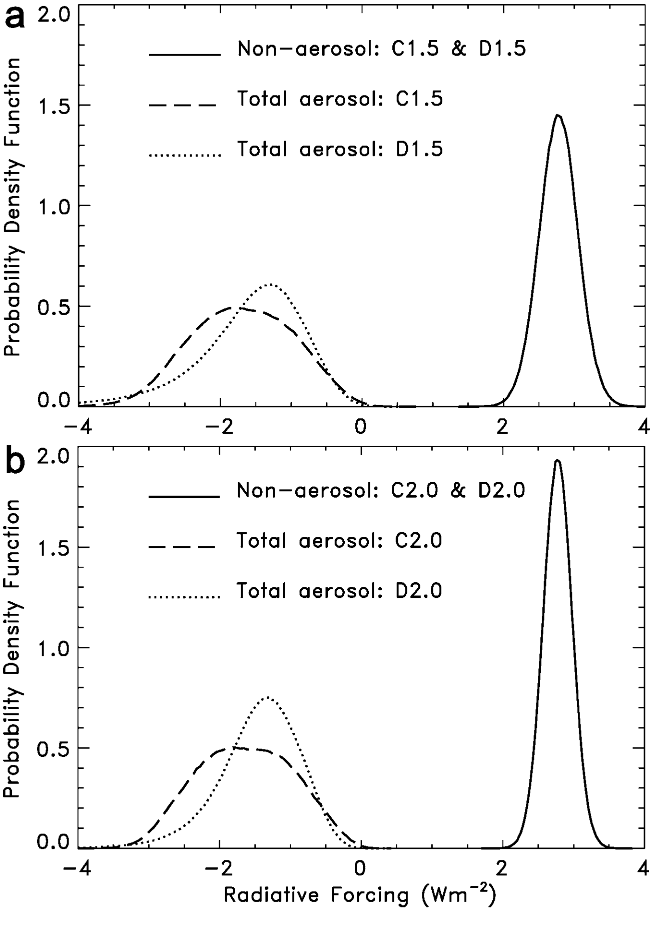

Fig. 4 Probability distribution functions of the total aerosol and non-aerosol radiative forcings for **a** scenarios C1.5 and D1.5 and **b** scenarios C2.0 and D2.0

select the C and D scenarios, the probability of a negative total RF is always less than 9% (i.e. the total RF is very unlikely negative or very likely positive). While analysis of climate variability and of temperature records suggests that the total RF is indeed positive (IPCC 2001), such arguments involve a degree of circular reasoning (Rodhe et al. 2000) and assume that our understanding of RF mechanisms, climate sensitivity, and climate response is complete.

Finally it should be noted that we only account for known RF mechanisms. In particular, we have excluded the second aerosol indirect effect from our analysis because too little is known about it (Ramaswamy et al. 2001). Since this RF is believed to be negative, its inclusion would increase the probability for a total negative RF and would correspondingly decrease the mean and median total RF. We plotted in Fig. 4 the PDF of the total aerosol and non-aerosol RFs for a subset of our scenarios (C1.5, D1.5, C2.0, and D2.0). It is clear that it is to a large extent the uncertainties in the aerosol RF which drive the large uncertainty in the total RF. We reiterate the conclusions of previous studies (Schwartz and Andreae 1996; Haywood and Boucher 2000) emphasizing that reducing these uncertainties should be a priority in order to improve climate change scenarios . It has been shown, for instance, that the determination of the climate sensitivity parameter, λ, is highly sensitive to the magnitude of the aerosol RF (Schlesinger et al. 1992). One possible direction for reducing the uncertainties could consist in a thorough analysis and comparison to observations of the different model estimates in order to select the most reliable ones.

Acknowledgements The authors are grateful to V. Ramaswamy and S. Schwartz for interesting discussions. Olivier Boucher thanks P. J. Crutzen, J. Lelieveld, and the MPI for Chemistry in Mainz for hospitality. We acknowledge K. Shine and the anonymous referees for their constructive remarks.

References

Charlson RJ, Schwartz SE, Hales JM, Cess RD, Coakley JA, Hansen JE, Hofmann DJ (1992) Climate forcing by anthropogenic aerosols. Science 255: 423–430

Cox SJ, Wang W-C, Schwartz SE (1995) Climate response to forcings by sulfate aerosols and greenhouse gases. Geophys Res Lett 22: 2509–2512

Forster PM de F, Blackburn M, Glover R, Shine KP (2000) An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. Clim Dyn 16: 833–849

Hansen JE, Sato M, Lacis A, Ruedy R, Tegen I, Matthews E (1998) Climate forcings in the Industrial era. Proc Natl Acad Sci USA 95: 12753–12758

Haywood J, Boucher O (2000) Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: a review. Rev Geophys 38: 513–543

IPCC (1990) Climate change 1990: the intergovernmental panel on climate change scientific assessment. Houghton JT, et al (eds) Cambridge University Press, New York, USA

IPCC (1994) Climate change 1994: radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios, Houghton JT, et al (eds) Cambridge University Press, New York, USA

IPCC (1996) Climate change 1995: the science of climate change, contribution of working group I to the second assessment report of the intergovernmental panel on climate change. Houghton JT et al (eds) Cambridge University Press, New York, USA, 572 pp

IPCC (1999) Intergovernmental panel on climate change special report on aviation and the global atmosphere. Penner JE et al (eds) Cambridge University Press, New York, USA, 373 pp

IPCC (2001) Climate change 2001, the scientific basis, contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Houghton JT, et al (eds) Cambridge University Press, New York, USA

Le Treut H, Forichon M, Boucher O, Li Z-X (1998) Sulfate aerosol, indirect effect and CO_2 greenhouse forcing: Equilibrium response of the LMD GCM and associated feedbacks. J Clim 11: 1673–1684

Meehl GA, Collins WD, Boville BA, Kiehl JT, Wigley TML, Arblaste JM (2000) Response of the NCAR climate system model to increased CO_2 and the role of physical processes. J Clim 13: 1879–1898

Myhre G, Myhre A, Stordal F (2001) Historical evolution of radiative forcing of climate. Atmos Env 35: 2361–2373

Penner JE, Andreae M, Annegarn H, Barrie L, Feichter J, Hegg D, Jayaraman A, Leaitch R, Murphy D, Nganga J, Pitari G (2001) Aerosols, their direct and indirect effects. In: Houghton JT et al (eds) Climate change 2001, contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York, USA, pp 289–348

Penner JE, Rotstayn LD (2000) Indirect aerosol forcing. Science 290: 407

Ramaswamy V, Chen C-T (1997a) Climate forcing-response relationships for greenhouse and shortwave radiative perturbations. Geophys Res Lett 24: 667–670

Ramaswamy V, Chen C-T (1997b) Linear additivity of climate response for combined albedo and greenhouse perturbations. Geophys Res Lett 24: 567–570

Ramaswamy V, Boucher O, Haigh J, Hauglustaine D, Haywood J, Myhre G, Nakajima T, Shi GY, Solomon S (2001) Radiative forcing of climate change. In: Houghton JT et al (eds) Climate change 2001, contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York, USA, pp. 349–416

Raper SCB, Cubasch U (1996) Emulation of the results from a coupled general circulation model using a simple climate model. Geophys Res Lett 23: 1107–1110

Rodhe H, Charlson RJ, Anderson TL (2000) Avoiding circular logic in climate modelling. Clim Change 44: 419–422

Schlesinger ME, Jiang X, Charlson RJ (1992) Implication of anthropogenic atmospheric sulphate for the sensitivity of the climate system. In: Rosen L, Glasser R (eds) Climate change and energy policy. American Institute of Physics, New York, pp 75–108

Schwartz SE, Andreae MO (1996) Uncertainty in climate change caused by aerosols. Science 272: 1121–1122

Shine KP, Fouquart Y, Ramaswamy V, Solomon S, Srinivasan J (1996) Radiative Forcing of Climate change. In: Houghton JT et al (eds) Climate change 1995: The science of climate change, contribution of working group I to the second assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York, USA, pp 108–118

Shine KP, Forster PM de F (1999) The effect of human activity on radiative forcing of climate change: a review of recent developments. Global Planet Change 20: 205–225